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Carbon storage and valuation of ecosystem services on a restored urban forest in Northeastern Illinois

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ABSTRACT Urban forests provide a multitude of different valuable ecosystem services, such as carbon sequestration and air pollutant removal. However, urban forests are also at risk due to negative impacts brought on by climate change and the increased presence of invasive species. In this natural experiment, 2 transects in Prairie Wolf Slough, Highland Park, Illinois were monitored over the course of 4 years in order to evaluate demographic changes. The estimated total whole tree biomass for the forest was calculated to be 115,420.4 kg in the year 2016 and 115,154.0 kg for the year 2020. The total amount of carbon stored decreased from 1,331.1 metric tons in 2016 to 1,328.0 metric tons in 2020. These declines in both stored carbon and whole tree biomass relate to an overall decrease in ash and elm trees, which could potentially be the result of the amplified presence of invasive species due to climate change, as well as forest restoration strategies.

INTRODUCTION

As mounting evidence of the detriments and dangers caused by anthropomorphic climate change have emerged in recent decades, scientists across disciplines have urged our institutions to take action to slow these negative impacts and to preserve our limited natural resources (Sohngen & Mendelsohn, 2003). The discipline of forest management is an example of one such attempt. Within the forest management discipline, the concept of restoration has been made a guiding principle in both policy and approach to managing for a healthy forest ecosystem.

The currently favored definition and guidelines for restoration have been set forth by The Society for Ecological Restoration International (SERI), an active and authoritative contributor to the field of restoration ecology. The SERI's eight principles which measure restoration success are as follows: (1) engagement of stakeholders, (2) drawing on many types of knowledge, (3)

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practice is informed by native reference ecosystems, while considering environmental change, (4) supporting ecosystem recovery processes, (5) recovery is assessed against clear goals and objectives, using measurable indicators, (6) seeking the highest level of recovery attainable, (7) gaining cumulative value when applied at large scales, (8) restoration is part of a continuum of restorative activities (Gann, et al., 2019).

Although these principles provide an assessment strategy for measuring restoration success, few projects have the ability to measure such success against these guidelines, as financial and temporal limitations often prevent in-depth studies. In practice, management policies rely heavily on principles (3), (4), and (6) in determining their successes, leading to more specific goals of reestablishing forest structures with heavy emphasis on native and endemic species (Wortley, Hero, & Howes, 2013). Because of these limitations, evaluating restoration success remains complex, as emerging goals may not be mutually compatible with one another, and potential detriments to ecosystem functions may be underrepresented (Larkin, et al., 2014).

Additionally, the assumptions that restoration equates to healthy ecosystem functioning in all management scenarios and that restoration occurs on a linear timeline with a clearly defined endpoint is not without flaws. In many forests it is impossible to return to an all-native state once invasive species have dominated and shifted the regime of the ecosystem, meaning that labor-intensive forest management practices must be ongoing to maintain progress. Often, these practices can be extremely costly in terms of economics and time, and ultimately lead to questions of whether the costs of restoration outweigh accomplishments (Cordell et al., 2016). We therefore evaluate forest benefits over time by measuring the climate change mitigating abilities of a given forest – valuation of forest ecosystem services. Ecosystem services as defined by Fisher et al. (2009), are “the aspects of ecosystems utilized (actively or passively) to produce human well-being.” Valuation of ecosystem services is crucial to creating and implementing forest management and policy, as it “allows for a more fair comparison of alternative scenarios by including all consequences.” (Klimas, et al., 2016). In the following case study, we investigate the ecosystem service of carbon storage and sequestration in a suburban forest, and report the change in ecosystem service provision over time. Carbon storage and sequestration is the process of capturing and storing atmospheric carbon dioxide, and in the case of forests, this carbon is stored in living biomass (Perschel, Evans, & Summers, 2007).

Ultimately, this case study aims to assess change in carbon storage and sequestration over a 4-year period. The site of the study is a protected natural area in Highland Park, Illinois, Prairie Wolf Slough (PWS). PWS has undergone restoration beginning in 1995 via removal of the invasive species *Rhamnus cathartica*, during which the site was monitored for native tree growth and mortality. The results presented here are a culmination of that monitoring and provide an approximation of what value of carbon sequestration services have been lost or gained during restoration. In addition to buckthorn removal, this area has seen evidence of tree death from *Agrilus planipennis* (emerald ash borer), an invasive species that has thrived and proliferated across the North American continent under climate change (DeSantis, et al., 2013). As both restoration and invasive species affect urban forests globally, this case study looks at the shift in carbon storage for one urban forest under invasive species and following historical buckthorn removal.

Researchers have demonstrated both that the presence and removal of the invasive species *Rhamnus cathartica* (European buckthorn) has largely detrimental effects on ecosystem functions and ecosystem services. Heneghan et al. (2006) found that the presence of *R. cathartica* alters soil properties in woodlands, and soils where *R. cathartica* is present have “higher percentages of N and C contents, an elevated pH, and higher water content” than soils where *R. cathartica* is absent. Mascaro and Schnitzer (2011) determined in their case study of a Southern Wisconsin forest that “*R. cathartica* can act as a forest canopy dominant… and that where

this occurs, aboveground biomass may be more limited relative to sites dominated by native species." Where aboveground biomass is limited, carbon sequestration will also be limited. Finally, in a case study most similar to this one, Larkin et al. (2014) found that "there were ecosystem changes associated with plant-community change in a previously buckthorn-invaded woodland… [and] higher rates of soil CO_2 efflux." We therefore expect to see that the removal of European buckthorn at PWS will result in a change in the forests ability to sequester carbon.
Valuation of carbon sequestration services at PWS is determined using the social cost of carbon (SCC). The social cost of carbon is a metric of both the costs associated with increasing one metric ton of CO_2 and the benefits of decreasing one metric ton of CO_2 in the atmosphere (Nordhaus, 2017). Using the SCC to estimate the value of surviving aboveground biomass, a determination can be made on the relative success of invasive species removal in monetary terms.

METHODS

To quantify the change in ecosystem services provided by trees within Prairie Wolf Slough, approximately 250 trees within three transects of the forest were measured in the years 2016 and 2020. Trees were identified by species and then labeled numerically. Dendrometer bands were placed on trees randomly within transects 1 and 2. These dendrometer bands monitored tree growth throughout these years (Klimas et al. 2016). Dendrometer bands are spring-loaded metal bands that wrap around the tree at 1.5 meters in height. As the tree grows, the spring extends, and the growth can be measured by the extension of the band. During the summer months of 2020, the diameter at breast height, (DBH) and the growth increment of the dendrometer band were recorded for the labeled trees within transects 1 and 2. Trees that could be identified as dead still had the DBH measured but were marked as dead as to not count their whole tree biomass in the final calculations.

Once the measurements for all trees were taken, there was data for a total of 241 trees. To begin, dendrometer band increase was first calculated. The initial dendrometer reading in 2016 was subtracted from the final reading to find the overall change in diameter. The diameter was converted to centimeters, and then summed with the initial tree diameter measurement to calculate the final DBH for trees in 2020. Whole tree biomass was then calculated from both initial and final DBH measurements. Whole tree biomass allometric equations were used to calculate these values, and there are different equations for different species. The list of allometric equations used were compiled from several sources: Nowak (1993), Tritton and Hornbeck (1982), Jenkins et al (2004) and Barros et al. (1999). For example, for oak trees, the equation for whole tree biomass is as followed:

$$Whole\ Tree\ Biomass\ (kg) = 0.113 * DBH\ (cm)^{2.4572}$$

$$Whole\ Tree\ Biomass\ (kg) = 0.113 * 37.7\ (cm)^{2.4572}$$

$$Whole\ Tree\ Biomass = 844.2\ kg$$

Whole tree biomasses for all trees measured within transects 1 and 2 were then to find the total whole tree biomass for the years 2016 and 2020. Trees that were recorded as dead were not included in the final calculations for whole tree biomass. Whole tree biomass values were then calculated for each individual species, such as oaks, elms, and ashes, in order to further analyze changes in ecosystem service properties.

Finally, estimated carbon storage for the entirety of the forest was calculated using the total whole tree biomass value. The sum for both initial and final whole tree biomass was converted from kg to short tons. Next, this value was multiplied by 0.5 to convert to the carbon equivalent, and then multiplied by 3.67 to get the amount of carbon dioxide. Finally, this value was then multiplied by 0.90718474 to get the value in metric tons, and then divided by 0.1591144039 to get the total amount of carbon stored for the urban forest that encompassed these transects, based on the percentage of the forest covered by the two transects. These carbon storage values in metric tons were then converted into monetary values based on the social cost of carbon (SCC), which is defined as the long-term damage as a result of the emission of a ton of carbon dioxide. These values were calculated by multiplying the calculated carbon storage value by the social cost of carbon at 3% and 5% discount rates for the years 2016 and 2020:

$$SCC\ (Dollars\ per\ Metric\ Ton\ CO_2) = CO_2 * 5\%\ Average$$

$$SCC\ (Dollars\ per\ Metric\ Ton\ CO_2) = 1{,}331 * \$12$$

$$SCC\ (Dollars\ per\ Metric\ Ton\ CO_2) = \$15{,}970$$

At a 5% discount rate, the social cost of carbon is $12, at a 3% discount rate, the SCC is $42. A 3% discount rate values the future, and its associated climate costs, more highly. Conversely, a 5% discount rate puts less value on these future climate costs (epa.gov). Through the utilization of discount rates, the monetary social cost of the carbon sequestered by trees in Prairie Wolf Slough can be determined.

RESULTS

The estimated sum of whole tree biomass for the urban forest, which was extrapolated from measurements taken from the two measured transects, was calculated to be 115,420 kg in the year 2016, while the sum for 2020 was calculated to be 115,150 kg. This is a percent decrease in biomass of 0.2%, showing a slight decline in whole tree biomass from 2016 to 2020. Table 1 displays the calculated initial and final whole tree biomasses for a number of different species, as well as the percent change in biomass.

	2016	**2020**	**Percent Change**
Elm	480	510	6
American Elm	1270	1330	5
Slippery Elm	3090	2030	-35
Ash	500	60	-88
Green Ash	2720	1800	-34
Black Ash	1360	910	-33
Oak	14650	11490	-22
Red or Black Oak	48010	52340	9
White Oak	26750	28580	7
Swamp White Oak	2980	3190	7
Chestnut Oak	4240	4250	0
Hickory	480	520	8
Shagbark Hickory	720	780	8
Mockemut Hickory	5570	5710	3
White Walnut	2240	2390	7
Black Walnut	760	500	-34
White Poplar	1390	1700	22

Table 1. Whole Tree Biomass (kg) for Individual Tree Species

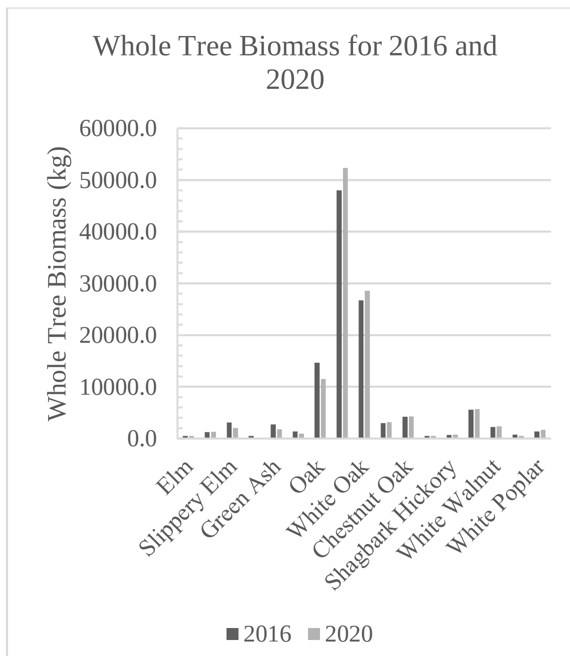

Figure 1. Bar graph displays whole tree biomass by species compared from 2016 to 2020.

Measured trees that fall under the oak category represented the largest percentage of total whole tree biomass. (Figure 1). Oak trees also saw an overall increase in whole tree biomass from 2016 to 2020. Conversely, ash trees saw the greatest decrease in whole tree biomass, with a decline of 88% over the 4-year period (Figure 2). For carbon sequestration, the initial estimated amount of carbon sequestered by the entire forest was calculated to be 1,331 metric tons in 2016, and 1,328 metric tons in 2020. This once again corresponds with a negative percent change in carbon storage by 0.2%. For initial measurements taken in 2016, the social cost of carbon according to the 3% and 5% discount rate calculated to be \$55,910 and \$15,970 respectively. For final measurements taken in 2020, the social cost of carbon according to the 3% and 5% discount rate calculated to be \$55,780 and \$15,940 respectively. Similarly, to whole tree biomass and carbon storage, the social cost of carbon also decreased overall from 2016 to 2020.

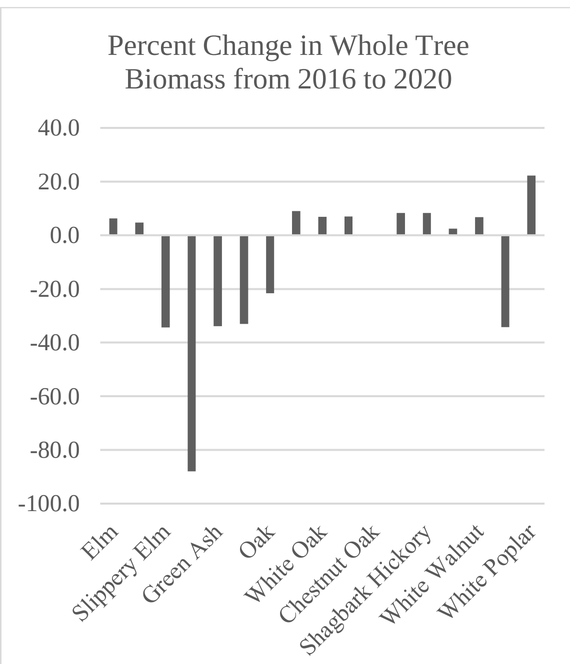

Figure 2. Bar graph displays percent change in whole tree biomass for a select number of species monitered.

DISCUSSION

The results of this natural case study suggest that tree mortality rates overtook additional tree growth at PWS. Of the nearly 300 trees measured in this experiment, 42 trees, or 14% of trees surveyed were recorded to be dead or dying throughout the time that the first and final measurements were taken. This high number of tree deaths is a large contributor to the decline in whole tree biomass of the entire site. There are many possible explanations for these results, principally impacts of global climate change and proliferation of invasive species, as will be discussed further below.

According to results, ash trees saw the largest negative change in whole tree biomass, and overall, ash species accounted for the largest percentage of tree mortality at PWS. These results make sense in the context of what we know about the invasive species, Emerald Ash Borer (EAB). Ash trees within the regions of the Midwest in recent years have been devasted by the presence of EAB, and this devastation has only grown as global climate change has caused average Midwestern temperatures to rise annually (Pryor, et al., 2014). The literature has shown that majority of overwintering EAB populations are unable to survive temperatures at or below -30° Celsius (DeSantis et al., 2013). With fewer calendar days reaching extreme low temperatures, EAB mortality has decreased, causing an increase in ash mortality. Therefore, decreases in whole tree biomass brought on by tree mortality can partially be explained by the presence of the invasive beetle.

However, ash trees are not the only species that saw a negative change in whole tree biomass throughout the course of this study. Results showed that elm and walnut trees have also seen decline in biomass and carbon storage. This decline may be due in part to the spread of Dutch Elm Disease, a wilt disease caused by the fungus *Ophiostoma ulmi* in forests across North America (Hubbes, 1999).

At PWS extensive restoration efforts to remove the invasive shrub *Rhamnus cathartica*, commonly known as buckthorn, have taken place duprior to this study. During plant removal, groundwater uptake decreases, leading to potential rise in the water table. A rising water table has been shown to deplete oxygen in the plant-root zone of the soil horizon and may also transport excess salts to the surface, contributing to plant dieback (ag.nsdu.edu). Although this study saw decreases in elm and walnut survival and growth in oak species, Robertson (1992) has shown rising water tables contributing to decreased growth rates of oak species in sites in Southern Illinois. While it is less likely that changes in the water table are responsible for the decreases seen in elm and walnut survival because of the aforementioned oak growth, further research into whether a rise in the water table at PWS in response to buckthorn removal may be worthwhile in order to fully determine if such a rise can be linked to increased elm and walnut mortality rates. This information will be vital in making restoration management decisions for PWS in its near future.

Overall, the results of this study recognize a pronounced shift in tree species demographics at PWS, as ash and elm species mortality rates increased while oak and hickory species have seen stable survival rates and increases in whole tree biomass. Although select native tree species have persisted, restoration removal decisions, the increased presence of invasive species, and global climate change remain critical to monitor and understand at this site if carbon sequestration is to be maximized.

Although restoration has been standardized as the foremost priority of forest managers in recent years, the results of this study reveal that it is essential to question and reevaluate our standard practices regarding restoration. Despite decades of ongoing restoration activity, relatively little progress in returning to an all-native state can be observed at the site. While this study proposes the use of ecosystem service valuation to measure healthy ecosystem functioning, it is far from comprehensive. It remains crucial that new methods of evaluating forest health develop and old methods and assumptions are checked as climate change and invasive species continue to impact these ecosystems.

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